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# MODELLING OF A SMALL SCALE RECIPROCATING ORC EXPANDER FOR COGENERATION APPLICATIONS

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## EXTENDED ABSTRACT

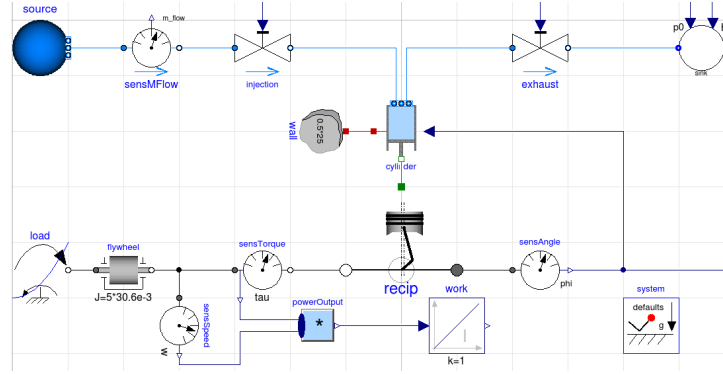
### INTRODUCTION

Various expansion machines are used in mini and small-scale organic Rankine cycle (ORC) installations. Among these, volumetric machines dominate with published work on, for example, vane-type (Mohd et al., 2010), reciprocating (Glavatskaya et al., 2012; Wronski et al., 2012) and scroll expanders (Lemort et al., 2011; Li et al., 2011; Wang et al., 2011) with the latter being the most commonly used device type. Most expanders run with fixed admission and exhaust timing causing over- and underexpansion, which leads to significant losses in off-design operation (Lemort and Quoilin, 2009).

This work presents dynamic models covering the operation of a reciprocating expander for a medium temperature heat source. Assuming a cogeneration scenario, condenser pressure of a power cycle changes with heat load. Here, the required temperature is varied from 25 °C to 75 °C representing the two cases of no heat demand and domestic hot water generation, respectively. To satisfy thermal demand at higher temperatures, the saturation pressure in the condenser has to rise since most heat is released during the phase change. This study considers the effect of elevated back-pressure on the closing of the admission valve concluding with an estimation for achievable power output under ideal operating conditions. As a result, a basic control scheme with variable valve timing based on condenser temperature only is sketched. Implementing the cutoff angle and condenser temperature relation in an algorithm helps to maintain a high isentropic efficiency  $\eta$  over a wide range of operating conditions.

### METHODS

This dynamic modelling study uses the Modelica language to simulate a reciprocating machine. A system consisting of fluid source, admission valve, expansion chamber, exhaust valve and fluid sink represents the flow path of the working fluid travelling from evaporator to condenser. The source holds an infinite amount of fluid at approximately 16 bar and 150 °C. Isenthalpic throttling occurs in both, inlet and outlet valve, accounting for fluid compressibility and the possibility of choked flow.



**Figure 1:** System used to simulate the impact of variable valve timing.

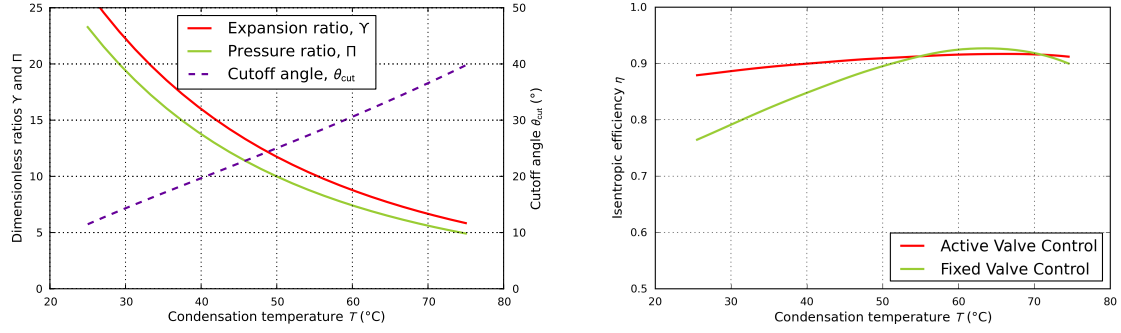
Starting from an initial guess value, state and mass of the working fluid in the cylinder are determined dynamically. Following the approach from the Modelica.Fluid and ThermoCycle libraries (Quoilin et al., 2013), the differential form of the mass balance and energy balance  $\dot{U} = \dot{H} + \dot{Q} + \dot{W}$  are solved continuously by the Dymola software. Besides the fluid related components, Figure 1 shows also the mechanical part of the model. A speed-dependent load is attached to a flywheel and the crankshaft of the reciprocating machine. The dynamic operation with alternating power and exhaust strokes leads to a varying rotational speed close to 1000 rpm for a fictitious expander design. The device is assumed to have a stroke and bore of 10 cm with a clearance volume of 20 cm<sup>3</sup> resulting in a maximum cylinder volume of approximately 805 cm<sup>3</sup>.

Operating with a fixed exhaust valve timing, the expander is controlled by the injection system only. Hence, the theoretical injection cutoff angle  $\theta_{\text{cut}}$  has to be determined as a function of condenser conditions. This cutoff angle describes the crankshaft position  $\theta$  at which the volume  $V$  in the cylindrical expansion chamber corresponds to the optimal expansion ratio  $\Upsilon$  for a given operating condition. Assuming saturation conditions in the heat exchanger, condenser pressure changes with temperature in a well-defined way as  $p_{\text{sat}}(T)$ . For n-Pentane as working fluid, CoolProp by Bell et al. (2013) provides accurate fluid properties enabling the calculation of the pressure ratio between vapour with 5 K superheat at  $T_{\text{ev}}$  of 150 °C in the evaporator and the pressure associated with condenser temperatures  $T_{\text{co}}$  of 25 °C to 75 °C. To find the right cutoff angle, the needed ratio of specific volumes, which equals  $\Upsilon$ , is used to find the correct pre-expansion volume of the cylinder and the associated distance  $x$  between piston and cylinder head. The equations

$$\Upsilon = \frac{V_{\text{max}}}{V_{\text{cut}}} = f(T_{\text{ev}}, T_{\text{co}}) \text{ and} \quad (1)$$

$$\theta_{\text{cut}} = f(x_{\text{cut}}) \text{ with } x_{\text{cut}} = f(V_{\text{cut}}) \quad (2)$$

summarise this procedure yielding  $\theta_{\text{cut}} = f(T_{\text{ev}}, T_{\text{co}})$  for a given geometry based on an isentropic expansion process from  $p_{\text{ev}}$  to  $p_{\text{co}}$ . To illustrate the impact of the concept described above, two simulations are carried out for the whole range of condenser temperatures. One expander is equipped with a variable valve control according to Equation 1 and Equation 2 while the other simulation employs a fixed  $\theta_{\text{cut}}$  that matches a  $T_{\text{co}}$  of 55 °C.



(a) Pressure and expansion ratio together with cutoff angle as functions of  $T_{\text{co}}$ . (b) Isentropic efficiencies of variable and fixed valve operation as functions of  $T_{\text{co}}$ .

**Figure 2:** Resulting cutoff angle and efficiencies.

## RESULTS

An illustrative result of the first steps of this analysis is displayed in Figure 2a. Here, the changes in saturation pressure and specific volume are expressed in terms of  $\Pi$  and  $\Upsilon$ , respectively. Both ratios decrease as the condenser temperature approaches evaporator conditions. To meet the desired expansion ratio, the cutoff angle has to behave in the opposite way stopping admission of working fluid between  $13^\circ$  and  $42^\circ$  crankshaft angle after top dead centre.

The data from Figure 2a can be used to derive a simple linear relation between condenser temperature in Kelvin and cutoff angle in radians

$$\theta_{\text{cut}} = -2.7 + 0.0097 T_{\text{co}} + z. \quad (3)$$

In order to use Equation 3 in the model, 0.2 was used for  $z$  to assure a certain amount of pressure difference between expansion chamber and exhaust system. Implementing the resulting function in a valve control system yields the first curve presented in Figure 2b. Both curves meet at the design temperature of  $55^\circ\text{C}$  while the actively controlled valves allow the compressor to run with an almost constant efficiency. Slightly above  $60^\circ\text{C}$ , the expander running with fixed valves exhibits a better performance than the one with controlled valves. This behaviour is related to the desired underexpansion caused by shifting the control function by the value of  $z$ . Setting  $z$  equal to 0 moves the maximum efficiency of the system with fixed valves to the design temperature. In such a case, both curves also meet at the design point temperature.

This work shows that a simple linear relation between condenser temperature and cutoff angle can help to assure a high expander efficiency even in off-design conditions. The presented system can maintain an isentropic expansion efficiency of approximately 90 % over the large pressure ratio range from 5 to above 20. However, the control has to be implemented carefully since conservative settings keep the system from performing at its maximum efficiency.

## LITERATURE

- I. H. Bell, S. Quoillin, J. Wronski, and V. Lemort. Coolprop: An open-source reference-quality thermophysical property library. In *ASME-ORC 2013 – 2nd International Seminar on ORC Power Systems*, 2013.
- Y. Glavatskaya, P. Podevin, V. Lemort, O. Shonda, and G. Descombes. Reciprocating expander for an exhaust heat recovery rankine cycle for a passenger car application. *Energies*, 5(6):1751–1765, June 2012. ISSN 1996-1073. doi: 10.3390/en5061751.
- V. Lemort and S. Quoillin. Designing scroll expanders for use in heat recovery rankine cycles. In *Proceedings of the International Conference on Compressors and their Systems 2009*, pages 3–12, London, Sept. 2009. Institution of Mechanical Engineers.
- V. Lemort, S. Declaye, and S. Quoillin. Experimental characterization of a hermetic scroll expander for use in a micro-scale rankine cycle. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 226(1):126–136, Nov. 2011. ISSN 0957-6509. doi: 10.1177/0957650911413840.
- J. Li, G. Pei, Y. Li, and J. Ji. Evaluation of external heat loss from a small-scale expander used in organic rankine cycle. *Applied Thermal Engineering*, 31(14-15):2694–2701, 2011. ISSN 13594311, 18735606. doi: 10.1016/j.applthermaleng.2011.04.039.
- M. Mohd, N. Tahir, and T. Hoshino. Efficiency of compact organic rankine cycle system with rotary-vane-type expander for low-temperature waste heat recovery. *International Journal of Environmental Science And Engineering*, 2(1):11–16, 2010.
- S. Quoillin, A. Desideri, I. H. Bell, J. Wronski, and V. Lemort. Robust and computationally efficient dynamic simulation of orc systems: The thermocycle modelica library. In *ASME-ORC 2013 – 2nd International Seminar on ORC Power Systems*, 2013.
- H. Wang, R. B. Peterson, K. Harada, E. Miller, R. Ingram-Goble, L. Fisher, J. Yih, and C. Ward. Performance of a combined organic rankine cycle and vapor compression cycle for heat activated cooling. *Energy*, 36(1):447–458, Jan. 2011. ISSN 03605442. doi: 10.1016/j.energy.2010.10.020.
- J. Wronski, M. J. Skovrup, B. Elmegaard, H. N. Rislå, and F. Haglind. Design and modelling of a novel compact power cycle for low temperature heat sources. In U. Desideri, G. Manfrida, and E. Sciubba, editors, *Proceedings of ECOS 2012*, Perugia, Italy, June 2012. Firenze University Press.